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The objective of this research is to obtain response and constitutive characterization for Concrete and mortar at strain rates up to 105s-1, to analyze the evolution of load-carrying and energy absorption capacities, and to understand deformation and failure mechanisms under high pressures. The high rate failure mechanisms considered include fragmentation, comminution and granular flow. Our investigation has focused on (1) the dynamic response of the "G"-mix concrete under impact conditions; (2) the effect of composite microstructure and aggregate reinforcement on the material stress-carrying capacity; and (3) the failure wave phenomenon in mortar under uniaxial-strain impact loading. Experiments and numerical simulations have shown that while the quasistatic uniaxial strength for the concrete is approximately 30 MPa, the average compressive stresses carried by the concrete under the conditions of impact experiments involving elastic steel target plates and impact velocities between 290 - 330 ma-1 is on the order of 1600 MPa. The marked increase in stress is attributed to the effect of higher strain rates which are on the order of 104s-1 and to the effect of lateral confining stresses. Experiments also showed that the stresses carried by mortar (matrix phase in concrete) under the same conditions are approximately 1200 MPa or 75% of that for the concrete (approximately 1600 MPa). Due to the composite microstructures and its relatively coarse aggregate size, the deformation and stresses are nonuniform inside the concrete.

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Progress and Final Report for the Project

"TIME-RESOLVED ANALYSIS OF THE DYNAMIC BEHAVIOR OF GRANULAR MATERIALS"

Grant Number: F49620-97-1-0055
Period Covered: January 1, 1997 - December 31, 1999

Min Zhou
Georgia Institute of Technology

Summary:

The objective of this research is to obtain response and constitutive characterization for Concrete and mortar at strain rates up to 10^5 s^{-1}, to analyze the evolution of load-carrying and energy absorption capacities, and to understand deformation and failure mechanisms under high pressures. The high rate failure mechanisms considered include fragmentation, comminution and granular flow. Our investigation has focused on (1) the dynamic response of the "G"-mix concrete under impact conditions; (2) the effect of composite microstructure and aggregate reinforcement on the material stress-carrying capacity, and (3) the failure wave phenomenon in mortar under uniaxial-strain impact loading. Experiments and numerical simulations have shown that while the quasistatic uniaxial strength for the concrete is approximately 30 MPa, the average compressive stresses carried by the concrete under the conditions of impact experiments involving elastic steel target plates and impact velocities between 290 - 330 ms^{-1} is on the order of 1600 MPa. The marked increase in stress is attributed to the effect of higher strain rates which are on the order of 10^4 s^{-1} and to the effect of lateral confining stresses. Experiments also showed that the stresses carried by mortar (matrix phase in concrete) under the same conditions are approximately 1200 MPa or 75% of that for the concrete (approximately 1600 MPa). Due to the composite microstructure and its relatively coarse aggregate size, the deformation and stresses are nonuniform inside the concrete. Finite element simulations have been used to analyze the effect of the composite microstructure on the behavior of the concrete and to delineate the conditions under which average stresses can be interpreted from the experiments. It is found that a propagation distance of approximately 12-13 mm in steel provides a good means to obtain a macroscopic ("average") measure of the stresses carried by the heterogeneous concrete under dynamic impact conditions. VISAR laser interferometry is employed to probe the tensile strength of impacted materials at different locations within the specimen. Experiments conducted do not provide evidence to support the theory of failure wave occurrence in mortar. While a threshold impact velocity is required to initiate the failure, a clearly defined failure front traveling behind the loading wave at a speed lower than the longitudinal wave speed is not observed. Instead, stress profiles measured by internal PVDF stress gauges show an attenuation of the stress pulse as it travels through the specimens, indicating the processes of microcrack growth and collapse of micro porosity commence with the arrival of the loading wave.

Introduction

The need to understand dynamic behavior of concrete and mortar at high strain rates is of critical importance in a range of applications including airport runways and structures subject to blast or penetration. Under such dynamic conditions, the strain-rate dependence of material response and high levels of hydrostatic pressure cause the material behavior to be significantly different from what is observed under quasistatic conditions. The dynamic deformation and failure of a G-mix concrete are analyzed experimentally and numerically. The experiments use plate impact and split Hopkinson bar. Normal impact experiments involving impact velocities up to 400 ms^{-1} are conducted. Experiments show that the stress-carrying capacity of the materials depends strongly on loading rate and hydrostatic pressure. Under conditions of quasistatic uniaxial stress, the strength for the concrete is approximately 30 MPa. Under the conditions of impact experiments involving elastic steel target plates and impact velocities between 290 - 330 ms^{-1}, the average compressive stresses carried by the concrete are found to be on the order of 1300 MPa. The marked increase in stress is attributed to the effect of higher strain rates which are on the order of 10^4 s^{-1} and to the effect of lateral confining stresses. Due to the composite microstructure of the concrete, the deformation and stresses are nonuniform in the experiments. The effect of material inhomogeneity on the measurements is analyzed numerically. The finite element simulations use a micromechanical model that explicitly accounts for the arbitrary material microstructure and constituent behaviors. The experimental data and material model provide a characterization of the behavior of concrete under strain rates between 10^{-3} to 10^5 s^{-1} and for pressures up to 2 GPa. A separate experimental investigation has been carried out to characterize the failure behavior of mortar under conditions of uniaxial strain. Experiments conducted so far do not provide evidence to support the theory of failure wave occurrence in mortar. While a threshold impact velocity is required to initiate the failure, a clearly defined failure front traveling behind the loading wave at a speed lower than the longitudinal wave speed is not observed. Instead, stress profiles measured by internal PVDF stress gauges show an attenuation of the stress pulse as it travels through the specimens, indicating the processes of microcrack growth and collapse of micro porosities commence with the arrival of the loading wave.

Experiments

The materials analyzed are a G-mix concrete with an average aggregate size of 9.5 mm and a pure mortar. Both materials have the same preparation conditions and the pure mortar has the composition as that of the mortar phase in the concrete. When tested separately, the pure mortar provides a means to obtain the response of the mortar phase in the concrete.

A plate impact experiment is used to obtain the response of concrete and mortar at strain rates above 10^4 s^{-1} under nominally plane strain conditions. Due to the composite microstructure of the concrete, stress and deformation are usually not uniform in the specimen. As illustrated in Fig. 1, this experiment is designed in such a way that an average measure of the stress-carrying capacity of the specimen material is obtained. Specifically during the experiment, the concrete specimen impacts a hard steel target plate which remains elastic throughout the experiment. An average stress at the specimen-target interface is $\sigma = \frac{1}{2}\rho c V_{fs}$, where V_{fs} is the particle velocity history at the rear surface of the target plate measured by a VISAR interferometer. The plate impact experiments are conducted on a helium gas gun. The specimens are 10 mm in thickness and 76.2 mm. The target is 13.5mm in thickness.

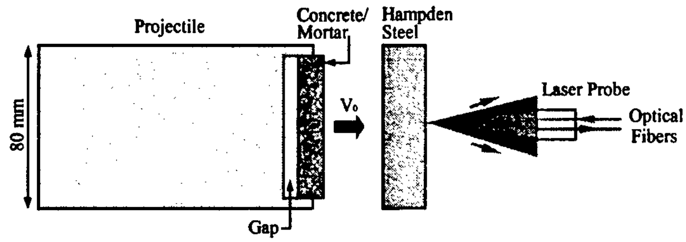

Fig. 1 Plate impact experiment on Concrete

Figures 2 and 3 show the results of two series of experiments conducted at impact velocities of 290 m/s and 330 m/s, respectively. The average stress carried by the concrete at both impact velocities is approximately 1300 MPa. The average stress carried by the mortar is approximately 90% that of concrete, or about 1175 MPa. These stresses are much higher than the maximum quasistatic stresses of attainable by these materials (approximately 30 MPa for concrete). The difference is attributed to the high strain rates (approximately 10^4 s^{-1}) and high confining stresses (approximately 1.2 GPa) in the impact experiments. The higher stresses carried by the concrete compared to the mortar indicates the hardening effects of aggregates in the concrete. The oscillations in the curves for the concrete suggest the stress is not totally uniform in the specimen due to material inhomogeneities.

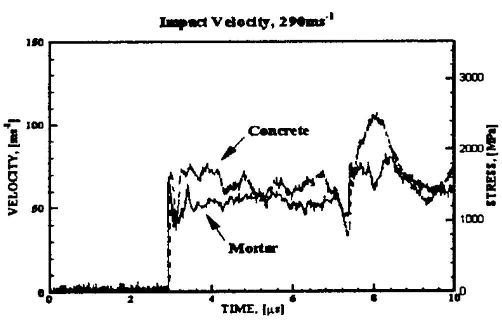

Fig. 2 Free surface velocity and stress profiles (V_0=290m/s)

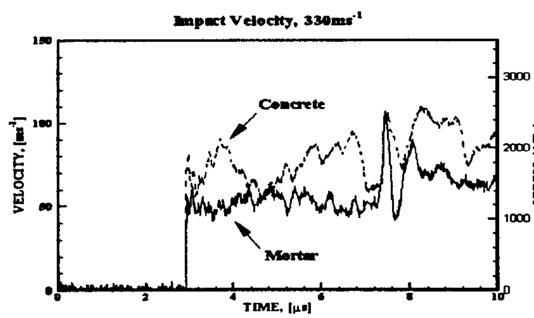

Fig. 3 Free surface velocity and stress profiles (V_0=330m/s)

In order to characterize the material responses over a wide range of strain rates, experiments are also conducted on mortar using a split Hopkinson pressure bar apparatus. The strain rates achieved in these experiments are between 6×10^2 and 1.4×10^3 s^{-1}.

Numerical Simulation

Based data from the impact and split Hopkinson bar experiments, the responses of both the mortar and the granite aggregates in the concrete are characterized by the Drucker-Prager model for granular materials. This model is chosen because its ability to describe the pressure sensitivity, strain hardening, and strain softening. There is a lack of complete experimental data, especially for the aggregates, in determining all the model parameters. In the analyses, some parameters are calibrated in such a way that best prediction is achieved for independent impact experiments on mortar as well as on concrete.

Results and Discussion

The analyses focus on the effects of microstructure on the response of concrete. To this end, seven different microstructural morphologies shown in Fig. 4 are used. All the microstructures have a grain volume fraction of 42%. Another series of calculations concerns the effect of aggregate volume fraction. The same microstructural morphology with five successively different grain volume fractions shown in Fig. 5 is used.

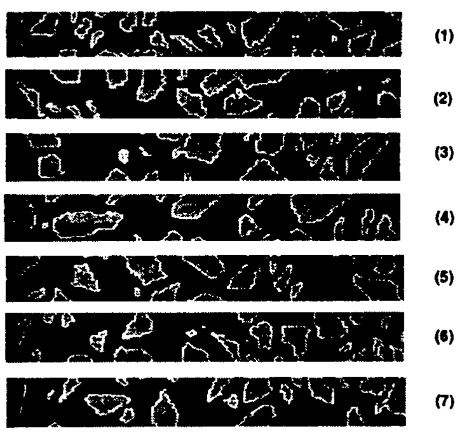

Fig.4 Different microstructural morphologies analyzed

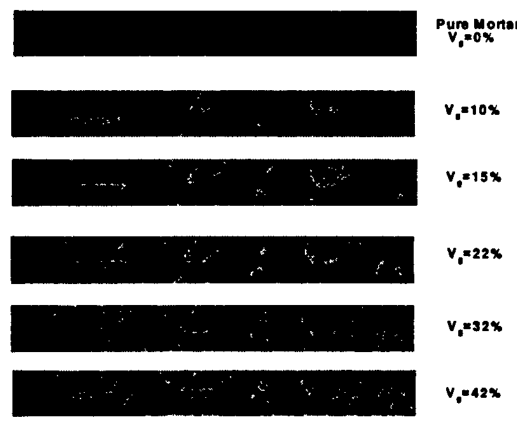

Fig.5 Microstructures with different grain volume fractions

Figure 6 shows the calculated distributions of equivalent plastic strain and stress component σ_{22} at 2.5 μs after impact using microstructure (4) in Fig. 4. It can be seen that most inelastic deformation occurs in the mortar matrix phase. Although both deformation and stress are non-uniform in the concrete specimen, the stress is essentially uniform near the rear surface of the elastic target plate. It is this uniform stress level that is used as a measure of the average stress carried by the specimen material during the impact experiment.

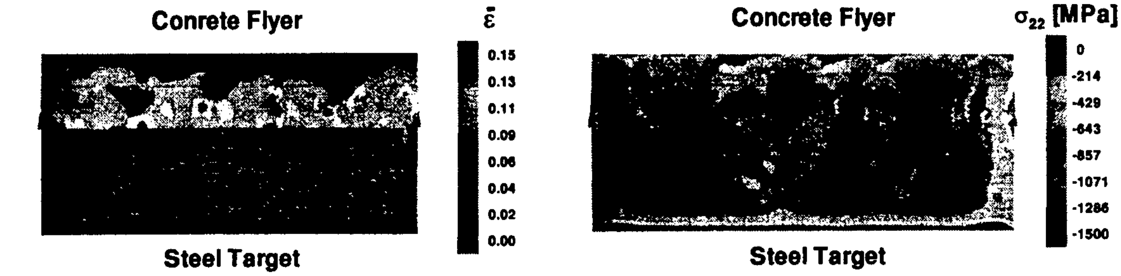

Fig. 6 Calculated distributions of equivalent plastic strain and stress component σ_{22}

A comparison of the measured velocity profile at the center of the rear surface of the target plate and calculated profiles for various microstructures is shown in Fig. 7. Figure 8 shows calculated velocity profiles for the microstructures in Fig. 5 with different grain volume fractions. Clearly, increasing the fraction of the grains strengthens the overall composite. Note that at a grain volume fraction of 42% (the actual ratio for the G-mix concrete used in the experiments) the calculated velocity level is approximately 10-15% higher than that for pure mortar. This is in line with what is observed in experiments, see Figs. 2 and 3.

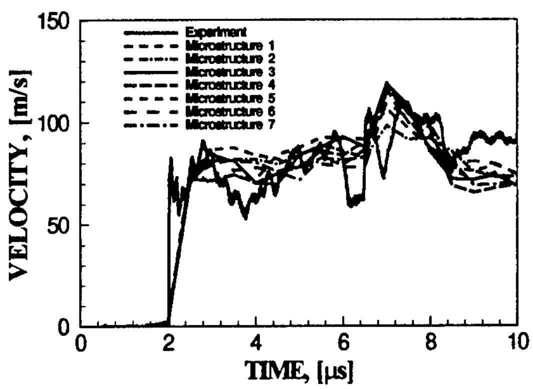

Fig. 7 Calculated and measured velocity profiles for different microstructural morphologies

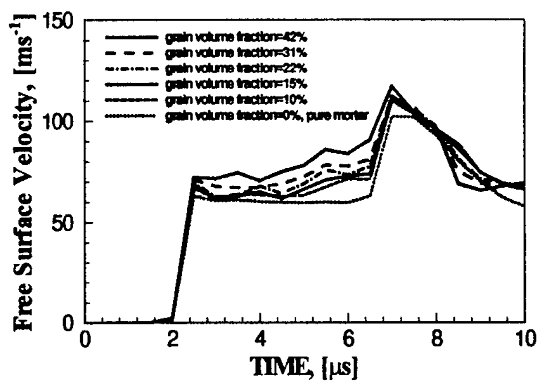

Fig. 8 Calculated and measured velocity profiles for microstructures with different grain volume fractions

The amount of variation in velocity in Fig. 7 is consistent with those measured during an experiment in which the velocity histories at four different points are recorded by a multiple beam VISAR system, see Fig. 9.

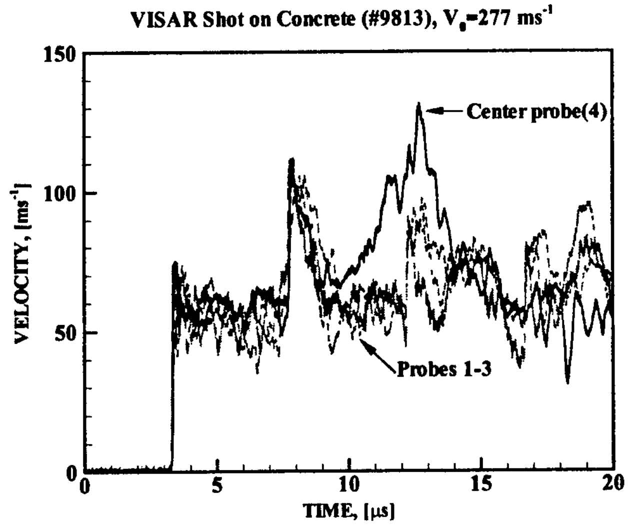

Fig. 9 Velocity Histories Measured at Four different Points on the target Surface

Failure wave Phenomenon

The failure wave phenomenon in glasses has been well documented and analyzed. This form of failure involves the complete loss of tensile strength under conditions of uniaxial compressive strains generated by planar plate impact. A clearly defined failure wave front propagating from the impact face toward the interior of the specimen is usually observed. This front separates intact materials ahead of it and failed materials behind it. This form of failure has been attributed to the initiation and growth of microcracks. So far, evidence for the failure wave phenomenon has been obtained almost exclusively from glasses which are dense, homogeneous and highly brittle. There have been conjectures concerning the existence of such failure waves in more inhomogeneous materials such as ceramics, mortar and concrete. An experimental study is carried out to characterize the failure behavior of mortar under impact loading. The objectives are to investigate the existence of failure waves in such materials and to provide data for modeling and simulation.

A series of plate impact experiments has been conducted. The specimens and the PMMA impactors are 3 inches in diameter. The experiments are designed to probe the tensile strength of impacted materials at different locations. A VISAR laser interferometer system is used to record the velocity histories at the center of the specimens. Recorded velocity profiles are used to infer the tensile strengths of the specimen materials ahead as well as materials behind possible failure wave fronts, Figs. 10 and 11. A second series of experiments are conducted, focusing on the propagation and attenuation of the stress waves as they traverse the impacted specimens. These experiments use embedded PVDF stress gauges to measure the longitudinal and transverse stress histories at the impact face and two other planes away from the impact face. Experiments conducted so far do not provide evidence to support the theory of failure wave occurrence in mortar, Fig. 12. The form of failure observed in specimens analyzed seems commence with the arrival of the loading wave. While a threshold impact velocity is required to initiate the failure, a clearly defined failure front traveling behind the loading wave at a speed lower than the longitudinal wave speed is not observed. Instead, stress profiles measured by the internal PVDF stress gauges show an attenuation of the stress pulse as it travels through the specimens, indicating the processes of microcrack growth and collapse of micro porosities commence with the arrival of the loading wave. The experimental measurements suggest that the failure process in mortar is gradual, in contrast to the sharply defined failure wave front in glasses.

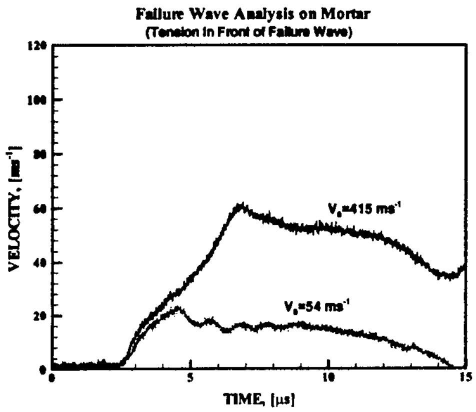

Fig. 10 Velocity profiles for experiments with tensile loading occurring in front of possible failure waves

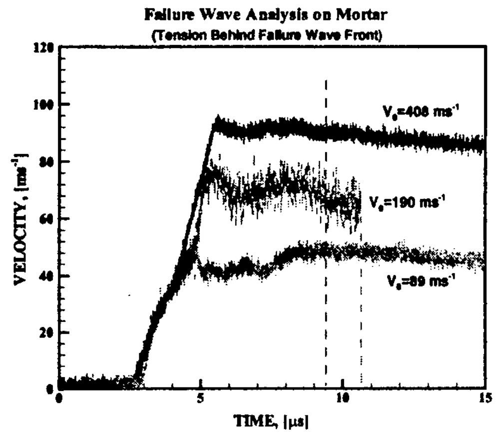

Fig. 11 Velocity profiles for experiments with tensile loading occurring in front of possible failure waves

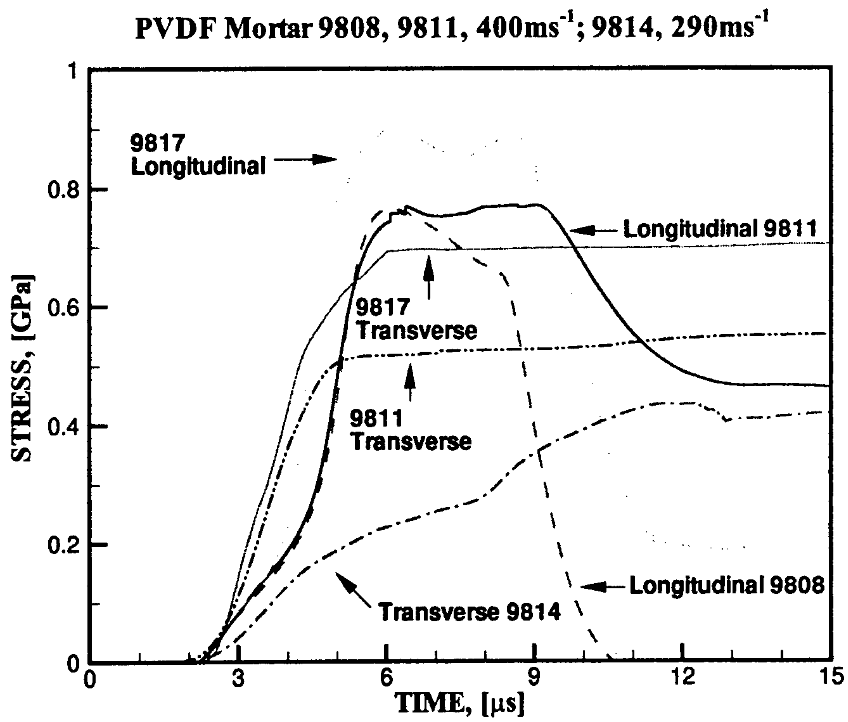

Fig. 12 Internal stress histories measured by PVDF gauges

Summary of Findings

Experiments have shown a variation of load-carrying capacity for the G-mix concrete from 30 MPa under quasistatic uniaxial stress conditions to approximately 1300 MPa under dynamic impact conditions with pressures up to 2 GPa. A constitutive characterization valid for strain rates between 10^{-3} to 10^{5} s^{-1} and pressures up to 2 GPa is obtained for the concrete. A micromechanical model for the dynamic behavior of concrete is developed based on the experimental characterization. Experiments and numerical simulations showed that the load-carrying capacity of the concrete is approximately 10-15% higher than that of the pure mortar. Experiments conducted so far do not provide evidence to support the theory of failure wave occurrence in mortar. While a threshold impact velocity is required to initiate the failure, a clearly defined failure front traveling behind the loading wave at a speed lower than the longitudinal wave speed is not observed. Instead, stress profiles measured by internal PVDF stress gauges show an attenuation of the stress pulse as it travels through the specimens, indicating the processes of microcrack growth and collapse of micro porosity commence with the arrival of the loading wave.

Students Supported:

Graduate Student	*Research topic*
D. Lucas Grote:	Time-resolved analysis of dynamic response using plate impact experiments
Qingxi Xia:	Finite element modeling of the dynamic deformation and failure of concrete

Undergraduate Student	*Responsibilities*
Kevin Starks	Specimen preparation, fixture design and manufactuering
Dawn Amos	Specimen preparation, conduction of experiment
Patrick Lesher	Digitization of concrete microstructure ABAQUS installation
Ken Len	Specimen preparation, lapping and polishing

Mr. Watkins is an African American. Miss Amos participated in the 1997 Georgia Tech SURF (Summer Undergraduate Research Fellowship program) while working on this project.

Publications/publications/Collaborations: (♦ incited talks)

1. D. L. Grote, S. W. Park and M. Zhou, "Dynamic Behavior of Concrete and Mortar at High Strain rates, Part I: Experimental Characterization", submitted to *International Journal of Impact Engineering*, 1999;

2. S. W. Park, Q. Xia and M. Zhou, "Dynamic Behavior of Concrete and Mortar at High Strain rates, Part II: Numerical Simulations", submitted to *International Journal of Impact Engineering*, 1999;
3. L. Grote, S. W. Park, and M. Zhou, "Experimental Characterization of the Dynamic Impact Failure Behavior of Mortar under Impact Loading", to be submitted to *J. Appl. Phys.*, 2000;
4. Dynamic Failure Resistance of Microstructurally Inhomogeneous Materials, Tsinghua University, June 10, 1999, Beijing, China; ♦
5. Micromechanical Modeling of Fracture in Heterogeneous Solids, *Sixth Pan American Congress of Applied Mechanics*, Rio de Janeiro, Brazil, January 4 - 8, 1999; ♦
6. Simulation of Dynamic Shear Failure in Metals with Account of Ductile Rupture Following Localization, ASME Mechanics and Materials Conference, June 27-30, 1999, Blacksburg, VA; ♦
7. Numerical Modeling of Fracture in Multiphase Ceramic Materials, 15th U.S. Army Solid Mechanics Symposium, April 12-14, 1999, Myrtle Beach, SC;
8. D. L. Grote and M. Zhou, An Experimental Characterization of the Dynamic Impact Failure of Mortar, American Physical Society (APS) 11th Topical Conference on Shock Compression of Condensed Matter, Snowbird, Utah, June 27-July 2, 1999;
9. S. W. Park, Q. Xia. And M. Zhou, Dynamic Behavior of Concrete at High Strain Rates, ACI 1998 Fall Convention, Oct. 25-30, 1998, Los Angeles, CA, with
10. Q. Xia, L. Grote and M. Zhou, Dynamic Deformation and Failure Behavior of Concrete at High Strain Rates, *Proceedings of the 12th ASCE Engineering Mechanics Conference*, pp. 1307-1310, 1998;
11. Q. Xia, L. Grote and M. Zhou, Dynamic Deformation and Failure Behavior of Concrete at High Strain Rates, by Q. Xia, L. Grote and M. Zhou, 12th ASCE Conference, La Jolla, CA, May 1998. This presentation is in addition to our presentation at the upcoming AFOSR granular materials/shock physics program meeting;

Collaborations:

1. The PI has been working with Dr. Zhen Chen from the University of Missouri-Columbia on the issue of failure waves in concrete. Data have been exchanged with Dr. Chen;
2. We have also worked with researchers at the Tyndall AFB on developing models for the dynamic behavior of concrete and mortar.